INTERFERENCE OF LIGHT AND SOME METHODS OF MEASUREMENT

BY

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I HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER MY SUPERVISION BY THERON BAYNE CHANEY

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FOREWORD

In preparing this thesis, the writer has had two objects in mind. The first one was to enlarge his own knowledge of the subject of interference of light waves.

The second one was due to the writer's interest in the field of high school teaching. Ten of the most widely used textbooks in high school Physics were examined to see how much space was devoted to the subject of interference. Three of the ten made no mention of the subject. Two of them gave two and one half pages to interference, while the rest averaged about two pages. This thesis has been written therefore with the high school student in mind, and this has made it necessary to include considerable detail which might not have been included otherwise. It is hoped that this discussion will awaken in a few worthy students a live interest in the subject of interference and will encourage them to delve more deeply into this subject, one of the most fascinating in the field of Physics. If this hope is realized, the discussion will have justified itself.

INTERFERENCE OF LIGHT

and

SOME METHODS OF MEASUREMENT

This discussion will be considered under four heads as follows:

1. A brief history of the development of the wave theory of light contrasting it with the then prevailing theory of light and including a short explanation of the theory.

2. A description of the experiments of Young and Fresnel and of other simple methods of producing interference of light leading up to a description and explanation of the Michelson interferometer.

3. An account of some experiments performed by the writer with the Michelson interferometer together with a description of some of the practical applications and some of the classical experiments in which this instrument has been used.

4. A description of some other well known types of interferometer including some of the most important applications which have been made of them.

I. Historical.

There have been a number of theories of the nature of light and the mode of its propagation from the time of the ancient Greeks down to modern times. Some of them were the result of much logical reasoning and withstood attacks from various philosophers for considerable lengths of time. Noteworthy among the modern theories of light was the corpuscular theory supported by Sir Isaac Newton. This theory postulated small luminous bodies which

were shot out in every direction from any luminous object, which, when they struck the retina of the eye, produced the sensation of sight. By making certain assumptions, this theory explained very satisfactorily the various phenomena which had been observed up to that time. Because of this fact, and also because of the great reputation of Newton as a scientist, this theory held its ground for a much longer time than it could have otherwise.

But the fact that new assumptions had to be made to explain newly observed phenomena with the corpuscular theory made it more or less unsatisfactory, and the undulatory or wave theory of light as developed by Huyghens was advanced in opposition to the older theory of Newton. This theory provided very satisfactory explanations of various phenomena without the necessity of making the assumptions which often had to be made with the other theory. For some time, there was considerable controversy over the relative merits of the two theories, and some very famous experiments were performed in an attempt to prove the superiority of one or the other of these theories.

Assuming the corpuscular theory to be correct, it became necessary to suppose that light traveled faster in a denser medium such as glass or water than in a rarer medium such as air. Just the reverse of this was true with the wave theory. An ingenious experiment by Foucault proved quite conclusively that light traveled with a slower velocity in water than in air. The result of this experiment provided strong proof for the wave theory, but in spite of it, the corpuscular theory remained much in favor long after Newton's time. About a century later, Thomas Young showed the interference of light, and his work together with that of Fresnel was the final blow which completely discredited the

corpuscular theory.

II. The Meaning of The Wave Theory.

Before discussing the work of Young and Fresnel, some consideration must be given to the meaning of the wave theory of light. For our purpose, we may define a wave as a progressive shape or form which is propagated through a medium by the regular periodic vibrations of the particles of which the medium is composed. Every one is familiar with the waves which travel across the surface of still water when it is disturbed. Energy is transmitted along the surface of the water by the waves, but the water itself does not move with them. Instead, the particles of water execute an oscillating motion as each wave passes by. Waves may also be illustrated by a rope which is attached to a fixed body at one end, the other end being held by the hand. If the hand is moved periodically up and down, waves will pass along the rope from the hand to the fixed end. These waves will be executed in a vertical plane when the hand is moved in a vertical line, and the energy which the waves carry along may be felt by grasping the rope firmly at the fixed end.

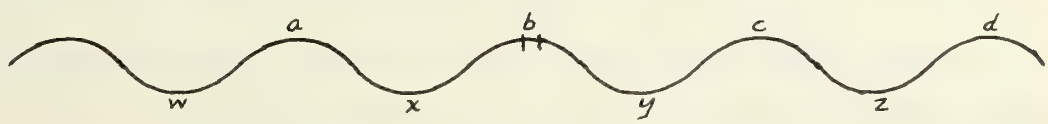

Figure 1.

Let Figure 1 represent the waves which travel along the rope. The points a, b, c, d, etc. are known as the crests of the waves, and the points w, x, y, z, etc. are called the troughs. Considering that the wave is traveling from left to right, let b represent a small section of the rope at the crest of a wave. An instant later, the crest of the wave will have moved forward, and

the trough w will now be immediately under the point where the crest was the preceding instant. But the section b of the rope has not moved forward, but has moved downward. An instant later, the crest a will have come along, and the section of the rope will have moved upward to its original position. Thus the small section of the rope is oscillating in a vertical line which is perpendicular to the direction of motion of the wave. The wave is therefore advanced by the oscillation of many sections of the rope, each one vibrating in a line perpendicular to the direction of the wave motion, and each one passing its motion on to the next section. It is important to note here that the energy transmitted to the rope by the hand is carried forward wholly by the wave itself, the sections of the rope retaining their relative positions throughout.

The wave theory of light is very aptly illustrated by the analogy of the rope waves given above. Light is a form of energy which is transferred by wave motion just as the energy which is communicated by the hand to the rope was transferred from one end of the rope to the other by the rope waves. But the rope waves have a visible medium by means of which they move forward, which is the rope itself, each section of the rope vibrating periodically in a line perpendicular to the direction of wave transmission. As far as the eye can tell, there is no such medium by which light waves may be transferred, but we know that it is transmitted through the air as well as through space in which there is no air. Obviously, if light consists of wave motion, there must be a medium filling all space which will transmit these waves. Such a medium is assumed to exist, although its

existence cannot be proved, and this medium is called the ether. It fills all space not occupied by other forms of matter. It is necessary to assume certain properties for the ether which are quite paradoxical. It must be a perfectly frictionless fluid which will offer less resistance to a body passing through it than the lightest known gas. But when a force is exerted upon a gas and some of the molecules are displaced from their original positions, they do not return to the original position when the force is removed. But in the case of wave motion, the particles must return to their position. Hence the ether must have great elasticity. Indeed, it is often spoken of as an elastic solid with the seemingly impossible property of being frictionless as already stated above. This then is the medium by which light energy is transferred as wave motion. As the light wave passes through the ether, each particle executes a periodic vibration perpendicular to the direction of motion of the wave in the same manner as each section of rope in a rope wave. Thus the light wave passes through the ether without the forward motion of the individual particles. This constitutes one of the main points of departure from the corpuscular theory. In this theory, the light energy is carried forward by small particles themselves, the particle actually moving forward in the direction of motion of the light ray.

Let us return for a moment to the analogy of the rope waves. Let Figure 2 represent the waves passing along the rope. The

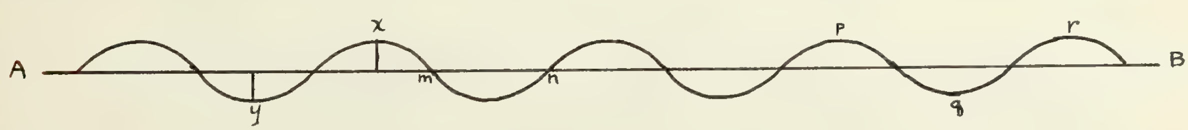

Figure 2.

line AB represents the rope when at rest. The perpendicular

distance from any crest x to the line AB is equal to the perpendicular distance from any trough y to the line AB. This distance represents the maximum displacement which a section or particle of the rope undergoes as the wave passes along the rope. This is the amplitude of the wave. The distance from any crest to the adjacent crest is one wave length, likewise from one trough to the next. The time taken for one wave length to pass a given point is the period. The portion of the wave through which a given particle has vibrated at the end of a certain time is called the phase. Any two particles which are separated from each other by a distance equal to half a wave length are in opposite phase. Thus consider two particles m and n as shown in Figure 2. They are a half wave length apart and are in opposite phase. If m is moving upward, then n is moving downward. Similarly, the points p and q are in opposite phase being separated from each other by a half wave length. But the points p and r are a whole wave length apart, hence they are in the same phase.

Suppose that at time = 0, a source of wave motion begins sending out waves. At the end of one second, it will have sent out N waves, and if each wave has a length l, the distance which the N waves will fill will be Nl. This means that the first wave will have traversed a distance equal to Nl in one second, and it will continue to do so in the succeeding seconds. This is the velocity v of the wave, and we may say that

$$v = Nl. \qquad (1)$$

Let us now consider for a moment waves on the surface of water. As the waves travel over the water, the particles of water take on an oscillating motion but do not move forward with the

wave. Suppose that we have waves coming from two sources A and B on the surface. They will spread out in all directions as shown in Figure 3. Let the waves from both sources have the same wave length, the same amplitude, and the same velocity. In the figure, the continuous lines represent wave crests, and the broken lines represent wave troughs. At the point x, two crests from the different sources meet. Hence the waves at this point are in the same phase, and the oscillating particles of the water take up energy from both waves so that its displacement is equal to the sum of the displacements which would be caused by either wave acting alone. Therefore, the crest will be higher here than the crest of either of the individual waves. Similarly, at the point y, two troughs are together, and the displacement of the water particles at this point is equal to the sum of the displacements caused by the two waves acting alone, so that the trough is deeper.

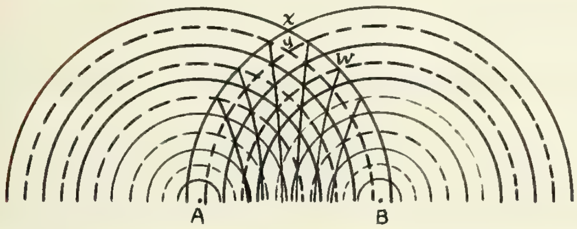

Figure 3.

Now let us see what happens at the point w where the crest of one wave meets the trough of the other. From our definition of phase as applied to rope waves on page 6, it is seen that these two waves are in opposite phase. Therefore the motion of one of the waves will tend to cause a displacement of the water particles in one direction, while the motion of the other wave will tend to produce a displacement in the opposite direction. The resultant displacement, being the sum of the two displacements of the two waves, will be zero since the motions of the two waves oppose or

annul each other. Hence the particles of the water will not move in either direction, and the surface of the water will remain quiet. From the figure, it is seen that there are other points besides the point w at which waves in opposite phase meet, and lines have been drawn through these points. These lines represent regions where the water is smooth and quiet, while between these lines are regions of maximum disturbance. When the waves meet thus in opposite phase, they are said to interfere with each other, and this phenomenon is known as interference. In contrast to this, the waves which meet in like phase are said to reinforce each other.

III. The Experiments of Young and Fresnel.

Sir Thomas Young proved the wave theory of light to be the correct one beyond all doubt when he showed the phenomenon of the interference of light. He knew that if light is propagated by wave motion, that there should be interference of the light waves under proper conditions. He therefore made some very famous, yet very simple experiments which proved his theory to be correct. One of his most noted experiments was as follows: He allowed light streaming through a very narrow slit S, (Figure 4) to fall upon two other narrow slits A and B which were parallel to the slit S, and were very close to each other. The slits are shown in the figure as being perpendicular to the plane of the paper. After passing through the slits A and B, the light was allowed to fall upon the screen PQ, and on this screen, the phenomenon of interference was observed. To

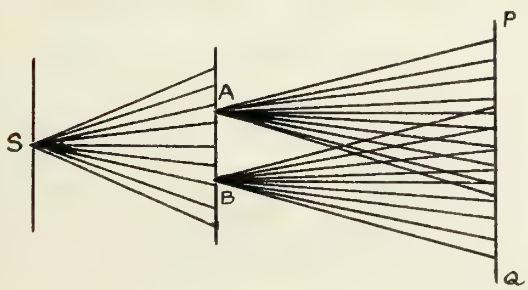

Figure 4.

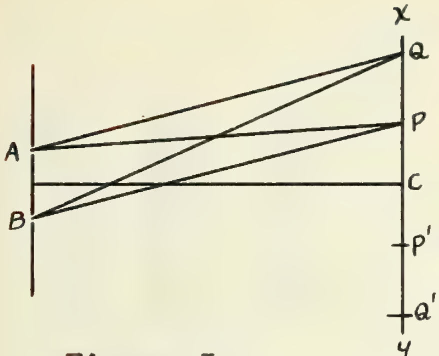

Figure 5.

show more clearly what took place, let A and B in Figure 5 represent the two slits through which the light passed. The light which passes through A at any instant is in the same phase as that which passes through B at the same instant. Let the light from the two sources meet on the screen XY at the point P, and suppose that the distance BP which the light which passes through B has traveled, is longer than the other path AP by half a wave length. Then these two wave trains will be in opposite phase at the point P and will therefore interfere with each other. Assuming that the light is of one single pure color, in other words, monochromatic or of a single wave length, there will be a dark band on the screen which is parallel to the slits A and B and which passes through the point P. Now consider the point C. It lies upon a line which is half way between the slits A and B and which is perpendicular to the plane in which the slits lie. Therefore C is equidistant from A and B, and wave trains of light from these slits will arrive at C in the same phase, and there will be reinforcement so that there will be a bright band through this point. By similar reasoning, it can be shown that there will be another dark band at P' which is on the opposite side of C from P. Now let us consider two more wave trains passing out from A and B along the paths AQ and BQ, and let BQ be longer than AQ by a whole wave length, or what is the same thing, by an even number of half wave lengths. Then at this point, the two wave trains will reinforce each other, and there will be a bright band passing through Q. By similar reasoning, it may be shown that there will

also be a bright band on the opposite side of C at Q'. Thus we

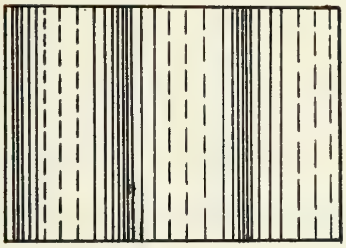

Figure 6.

will have alternate bands of interference and reinforcement on the screen, and the field will resemble the illustration in Figure 6. These alternate bright and dark bands are called interference fringes. This phenomenon may perhaps be made somewhat clearer by studying the geometry of Figure 7. Let P be a point on the screen

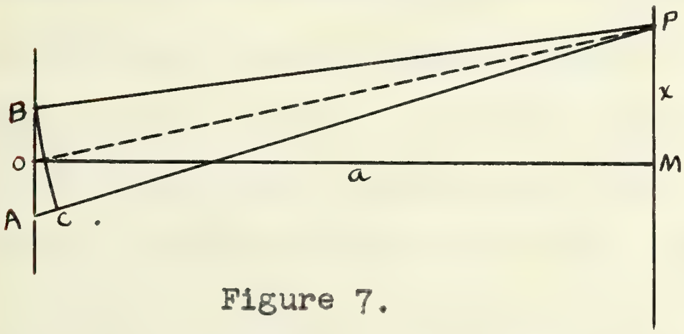

Figure 7.

such that the distance AP is n half wave lengths greater than the distance BP, or if l = the wave length,

$$AP - BP = n\frac{l}{2} \qquad (2)$$

Let the distance MP = x, and let OM = a. Then with P as the center and with PB as the radius, draw the arc BC. Since in the actual experiment, the slits A and B are very close together compared to the distance PB, the arc BC will be approximately a straight line perpendicular to OP. Now AB is perpendicular to OM, so that we have two angles ABC and MOP, which are equal, because the sides of one are perpendicular to the corresponding sides of the other. Since these angles are equal, the two right triangles ABC and MOP are similar to each other. Then we may say

$$\frac{PM}{OM} = \frac{AC}{BC} = \frac{AC}{AB} \qquad (3)$$

since AB is very nearly equal to BC. Let AB = c. AC is the difference between AP and BP which has been shown above in (2) to equal nl/2. Therefore

$$\frac{PM}{OM} \text{ or } \frac{x}{a} = \frac{n\frac{l}{2}}{c} \qquad (4)$$

and from equation (4),

$$x = \frac{a}{c}.\frac{nl}{2} \qquad (5)$$

This equation gives the distance x which any fringe may be from the point M on the screen which lies on the perpendicular bisector of AB. Now suppose that in equation (5) n = 0. Then the whole right hand side of the equation is equal to zero or x = 0. This means that the difference in length of the paths AP and BP has become zero, and the point P will now coincide with M. Light waves coming from the two sources A and B will therefore be in the same phase when they meet at M, and there will be a bright fringe or band on the screen passing through M. This is called the central fringe. We have already seen that when the difference in path of the two wave trains is equal to an odd number of half wave lengths, that the waves will be in opposite phase and will therefore cause a dark fringe. Therefore when n in (5) is an odd number, x will be the distance of the nth fringe from the central fringe, and this fringe will be dark. Likewise, if n is an even number, x will be the distance of a bright fringe from the central fringe, and it will be n fringes from the central one counting both bright and dark fringes. This reasoning holds good for light of a single wave length.

Suppose that we have white light which is made up of the various colors of the rainbow, or more correctly, the spectrum. From equation (5), it is seen that the distance x is proportional to the wave length l. Let n be an even number so that P (Fig. 7) will be a bright fringe. Now the wave length of red light is much longer than that of violet light. If we substitute the wave length of red light for l in (5), it is seen that the distance x

will be greater than it would be if the shorter wave length of violet light were substituted for l. Hence the fringe will vary in color from the red to the violet of the spectrum, and the violet edge of the fringe will be nearer to the central fringe than the red edge, because the violet wave length is shorter. Therefore for white light, instead of having bright and dark fringes as in the case of monochromatic light, we have rainbow colored fringes separated by dark spaces, the inner edge of each fringe being violet and the outer edge being red. The other colors of the spectrum whose wave lengths lie between those of the red and violet will also be seen in the fringe, each merging gradually into the other.

The explanation of Young's simple experiment here has been dwelt upon at some length, because it furnishes a foundation for understanding other applications of the principle of interference. It should be noted from this explanation that in order to produce interference, there should be two sources of homogeneous light, the light proceeding from each source in exactly the same phase. The slits A and B in Figure 4 are considered as sources, so the light which falls upon A and B must come from the same primary source, such as S, so that the waves proceeding from A and B may be exactly alike at any given instant. It should be mentioned here that Grimaldi tried this same experiment about 150 years before the time of Young. He made the mistake of allowing the light to fall directly upon the slits A and B without first passing it through the slit S. Hence the light which passed through A and B was not homogeneous, and he failed to observe true interference of light. In addition to having homogeneous light, there must also be a difference in path of any two wave trains passing from

A and B to a point P equal to an even number of half wave lengths for a bright fringe or to an odd number of half wave lengths for a dark fringe. These are the conditions necessary for interference.

Besides Sir Thomas Young, the other great physicist whose name is most intimately connected with the principle of interference in its early development is Fresnel, a Frenchman. Fresnel produced interference fringes in several different ways, two of which will be explained here. In the first method described here, he used two plane mirrors inclined to each other at an angle of nearly 180 degrees, so that they almost lay in the same plane as shown in Figure 8.

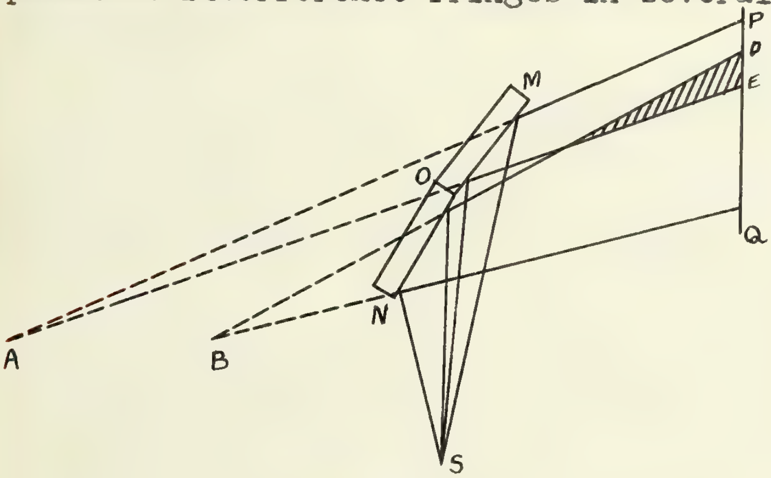

Figure 8.

ON and OM are the two mirrors. S is a source of light in the form of a narrow slit which is parallel to the dividing line between the two mirrors. The light from S which strikes ON is reflected toward the screen PQ as if it originated at the point B which is really the reflected image of the luminous slit in the mirror ON. Light which strikes OM is also reflected to the screen PQ as if it originated at the point A which is the reflected image of the slit in the mirror OM. It is seen that the light from the two virtual sources A and B, overlaps in the shaded portion just the same as the light overlapped from the two slits A and B in Young's experiment. (Fig. 4). Therefore the area DE of the screen covered by these overlapping fields of light will be

crossed by interference fringes. In this, as in Young's experiment, we have two sources of light A and B, and we know that the light waves proceeding from these two sources at any given instant are in the same phase, because the sources are images of the real source of homogeneous light. Various points on the screen between D and E are at different distances from A and B, so that at some points, bright fringes will appear while at others, there will be dark bands.

Fresnel produced interference in another manner by means of what has since been known as the Fresnel Bi-prism. The bi-prism is illustrated in Figure 9. It consists of two glass prisms placed together base to base at E. The angles at C and D are very small so that the angle at E is very nearly a straight angle.

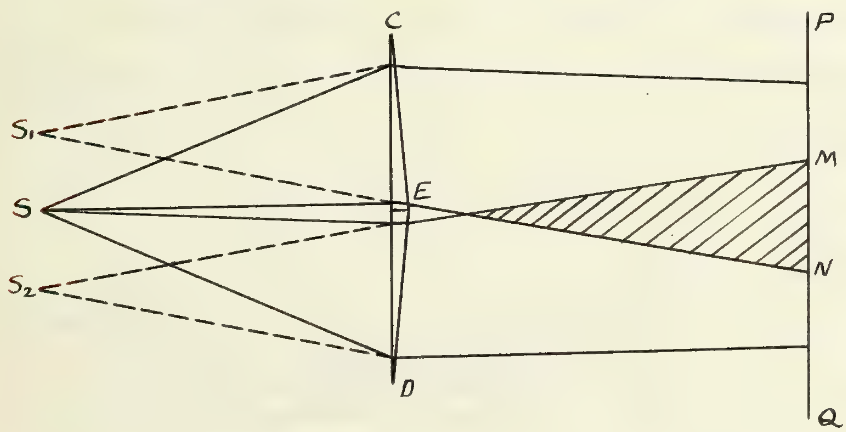

Figure 9.

Light from a slit S falls upon the back of the two prisms. That which falls upon the upper prism is refracted downward and proceeds to the screen PQ as if coming from a source S_1. That which passes through the lower prism is refracted upward and proceeds to the screen as if coming from a source S_2. It is seen that the diverging beams from these two virtual sources overlap each other as shown in the shaded area of the figure, and where these overlapping beams strike the screen, fringes will be formed. These two methods of Fresnel were an advance over Young's experiment, because they provided two sources of light very close together without the aid of any

apertures or sharp edges which might cause other effects besides interference. In fact, some of Young's contemporaries rather doubted his conclusions, because he used the two slits or apertures having sharp edges. It had already been observed that light, passing through a very small opening or past sharp edges, was diffracted, forming fringes very similar to interference fringes, and it was thought by some that Young had observed this diffraction effect instead of true interference. But Fresnel's work with his mirrors and bi-prism showed quite clearly that Young's conclusion was correct, and that he had actually obtained interference fringes.

Mention should also be made of a method of producing interference fringes due to Dr. Lloyd of Trinity College, Dublin. This method is known as Lloyd's single mirror method and was first described by him in 1834. A long, highly polished mirror is used. (Fig. 10). Light, from a source S in the form of a narrow slit, is allowed to fall upon the mirror at almost a grazing angle, that is, the angle of incidence is very nearly ninety degrees. It is then reflected in a diverging beam towards the screen PQ as if it originated at a point S_1, which is the reflected image of S in the mirror. Light coming directly from the source also strikes the screen, and the two beams overlap each other as shown by the shaded area. Hence these two overlapping beams produce interference fringes on the screen in the same manner as they are produced by Fresnel's mirrors or bi-prism.

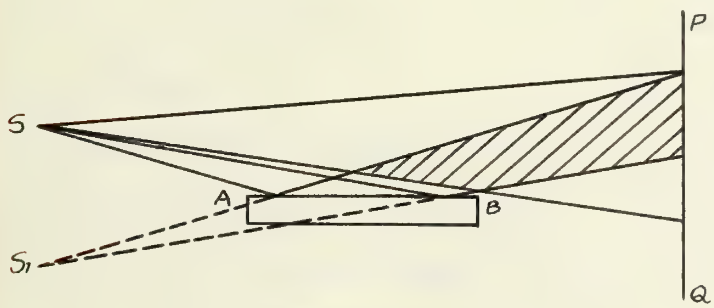

Figure 10.

IV. Interference By Thin Films.

We shall now take up briefly a study of the colors produced by very thin films, these colors being formed by interference of light waves. The following experiment will aid in understanding this phenomenon. Take two pieces of optically plane glass which have been carefully cleaned and are free from dust, and both of which are one or two inches wide and four or five inches long. Lay one piece on the other and clamp them together loosely at one end. Between the two plates at the opposite end, place a single silk fiber or a bit of tissue paper, and pressthe two plates together firmly. (Fig. 11). Then we have a very thin wedge of air between the two plates. The figure is very much magnified in order to show the principle more clearly. It is seen that the air wedge widens at a constant rate from the top to the bottom. Let S be a source of monochromatic light such as a sodium flame. Light proceeding from this source will strike the glass and some of it will pass clear through both plates, while some of it will be reflected from each of the four surfaces. In this experiment we are concerned only with the light which is reflected from the two inner surfaces, AB and AC. Hence there will be two wave trains of light superposed upon one another which are reflected from AB and AC in the direction OP. Now from an inspection of the figure, it is seen that the wave train which is re-

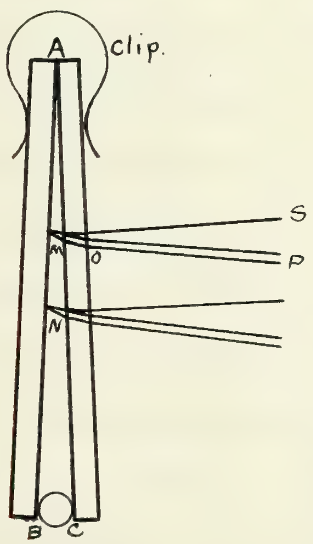

Figure 11.

flected from the surface AB, has traveled a greater distance than the wave train which is reflected from AC. If this difference in path is such as to make the two emerging wave trains in opposite phase, they will annul each other, and a dark band will be seen across the plate at this point. On the other hand, if the difference in path of the two wave trains is such that they emerge in the same phase, they will reinforce each other, and a bright fringe will be seen on the plate. Now we know that for two wave trains to interfere with each other, there must be a retardation of one behind the other by a half wave length, or an odd number of half wave lengths, so that they will be in opposite phase. Hence it would seem that interference would take place at a point where the distance through the air wedge and back is a half wave length or an odd number of half wave lengths. Likewise, for reinforcement, the distance through the wedge and back should be a whole wave length or an even number of half wave lengths. But just the opposite of this is found to be the case. Why this should be so is easily explained. It is a well known fact that when light waves, passing through a given medium, air for example, strike a denser reflecting medium such as glass, they suffer a change in phase of a half period upon reflection. That is, a crest of a wave will be reflected back as a trough and vice versa. But if the wave train is passing through glass and is reflected back from a rarer medium such as air, it will not suffer this change in phase. Now suppose that the distance through the air wedge and back at the point M (Fig. 11) is one half of a wave length. This will retard the wave train reflected from AB one half wave length behind the train reflected from AC. But the wave train reflected from AC is reflected from an air surface which is rarer than the

glass which it has just passed through and therefore suffers no change in phase. The other wave train has been reflected from a glass surface after passing through the air wedge, so that it has undergone a change in phase of half a period. This change added to that produced by the thickness of the air wedge retards this wave train one whole wave length behind the other one, so that they both emerge from the plate in the same phase and reinforce each other. Now consider a point N (Figure 11) farther down the air wedge where the thickness through the wedge and back is one whole wave length. Then one wave train will be retarded behind the other by a wave length, but as in the case above, it will also undergo a change of phase of half a period so that it will emerge from the glass one and one half wave lengths behind the first wave train and will thus interfere with it because it is in opposite phase. Therefore, we must conclude that where a dark band is seen across the plate that the distance through the wedge and back is at least one wave length or an even number of half wave lengths. Likewise, where a bright band is seen, the distance through the wedge and back will be at least a half wave length or an odd number of half wave lengths. When the light falls perpendicularly upon the first plate, the distance through the air wedge may be expressed as

$$d = n \cdot \frac{1}{2} \cdot l \qquad (6)$$

For light which does not fall perpendicularly upon the plate, the above equation is only approximately true. In such a case, the accurate expression involves a trigonometric function of the angle of incidence. Equation (6) gives the distance which the wave train travels in passing through the air wedge and back again. Clearly then, the thickness t of the wedge is one half

of this distance or

$$t = \frac{n \cdot \frac{1}{2} \cdot l}{2} = \frac{nl}{4} \quad (7)$$

In equation (7), l is the wave length, and when n is an even number, the expression gives the thickness of the wedge at a point where interference takes place. When N is odd, t will be determined for a point where reinforcement takes place. Since the air wedge widens at a constant rate, it is evident that there will be a number of points between the top and the bottom of the wedge where interference and reinforcement will alternately take place. n for any particular fringe will be its number from the top of the wedge down counting both dark and bright fringes. Thus for the first, second, third, etc., bright fringes, n will be equal to 1, 3, 5, etc., and for the first, second, third, etc., dark fringes, n will be equal to 0, 2, 4, 6, etc. This experiment is not very hard to perform, and the fringes may be easily seen with the naked eye if the eye is in such a position as to receive the light reflected from the plates. The experiment is very interesting and very instructive.

It has been assumed thus far that in this experiment, light of only one color is used as the light from the sodium flame. Suppose that white light is allowed to fall upon the plates. Then a series of rainbow colored fringes will be seen separated by dark bands or fringes. Let us consider one of the bright fringes for which n in equation (7) will be an odd number. Then for this particular fringe, n is a constant, and l is the only variable. The thickness t will therefore be proportional to l. Since the fringe has width, it follows that t will be greater at the bottom edge of the fringe than at the top. Therefore the wave length

of the light which is seen at the bottom edge of the fringe must be longer than that of the light at the top edge of the fringe. It will be observed that the lower edge of the fringe is red while the upper edge is violet. This furnishes proof therefore that the red end of the spectrum has longer wave length than the violet end. Another way of showing this is to interpose a piece of red glass between the source of white light and the plates. Thus only red light will fall upon the plates and only red fringes will be seen with dark bands between each two. The number of fringes, both bright and dark, should be counted, and their distance apart should be observed. Now interpose a piece of blue or green glass between the source and the plates. Blue fringes will now be seen, or green ones as the case may be, and it will be observed that they are closer together, and that there are more of them than for red light. This shows then, that the wave length of either the blue or the green light is shorter than that of the red.

With this simple piece of apparatus and by use of equation (7), the wave length of monochromatic light may be roughly approximated. Let the plates be illuminated with yellow light from a sodium flame. Count the number of fringes from the top to the bottom of the plates, both dark and bright ones. This will give n of equation (7). Then with a micrometer microscope, measure the thickness of the base of the air wedge. This will be t. We may substitute these observed values in the equation and solve for 1, the wave length. Let us suppose that the number of fringes counted is 24, and that the thickness of the wedge was found to be .0035 millimeter. Substituting these values in equation (7), we have

$$.0035 = \frac{24\ 1}{4} = 6\ 1$$

And $$l = \frac{.0035}{6} = .000583 \text{ millimeter}$$

which is a fairly close value for the wave length of sodium light considering the crudity of the apparatus.

Considerable space has been given to the explanation of this simple piece of apparatus, because it furnishes the explanation to many phenomena which we see everyday. A very simple experiment which any one can do is as follows: Take a piece of wire and bend it into a small loop with a handle at one side. Dip the wire into a prepared soap solution, and on taking out, a soap film will be stretched across the wire loop. At first, the film will be of uniform thickness throughout, but if held vertically, the liquid in the film will run down to the base, so that the thickness of the film will increase toward the bottom. Thus we have a wedge of the soap solution instead of a wedge of air, and light will be reflected from both surfaces of the film causing interference to take place. White light thus reflected will be seen as very beautiful colors varying from the red to the violet end of the spectrum. As the liquid of the film is constantly draining to the bottom, the positions of the colors will be changing continuously which adds much to the beauty of the effect. As the top of the film gets thinner and thinner, it will eventually become black. When the black area appears, the film is so thin that it soon breaks. In fact, it is so thin that the distance through it and back is practically zero, so that there is no retardation of one wave train behind the other. But one wave train is reflected from a denser medium than that through which it has passed, so that it suffers a change of phase of half a period. The other wave train does not suffer this phase change, because it is reflected from

a rarer medium. Hence the two wave trains are in opposite phase and therefore interfere with each other thus producing the dark region on the film.

Thus far, the fringes which we have discussed which are produced by thin films, have been straight fringes extending across the field of the film. A very simple experiment will show frimges produced in the same way which are circular. Take a piece of clean plate glass and lay it where light from the sky (not direct sunlight) will be reflected from it. Lay a thin piece of glass such as a microscopic cover glass upon the plate and then press down upon the center of the cover glass with the point of a needle or a pin. A very slight pressure is all that is needed to produce circular colored fringes with the pin point as the common center of the circles. If there are slight irregularities in the surface of the glass, the fringes may not be truly circular, but they will be closed curves. Sir Isaac Newton made a very complete study of such fringes, and they are therefore known as Newton's rings. He produced these rings by laying a convex lens, (Fig. 12) which had a very long radius of curvature, upon a plate of glass. The lens touched the glass plate at the point C. Now the lens diverges away from the plate at all points from the center out to the edge. Thus we have what might be termed a circular air wedge. The loci of all points on the curved surface of the lens, which are equidistant from the plate, are circles. Let light from a source S fall upon the plane side of the lens. Some of it will pass through and will be reflected at the point P

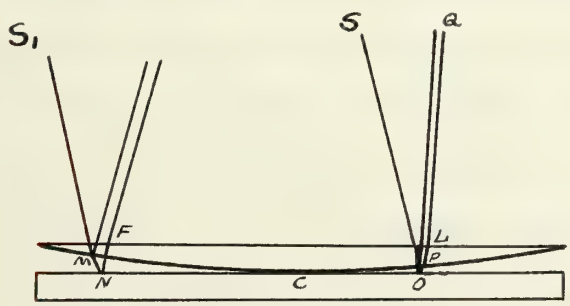

Figure 12.

on the convex surface of the lens. Part of the light will also pass on to the plateand will be reflected at the point O of the plate. Both wave trains will be reflected in the direction OQ. As in figure 11, one wave train will travel a greater distance than the other, and if this distance is such as to cause the two waves to emerge from the lens at L in opposite phase, they will interfere with each other thus causing darkness. Now there will be a large number of pairs of points as O and P for which the distance between each pair will be the same, and these points will all lie in a circle about C as the center. Hence there will be a dark ring caused by interference at all these points. Let us consider two points further out on the lens and plate such as M and N. Here the distance between M and N will be such that the two wave trains will emerge from the plane surface of the lens at F in the same phase and will therefore reinforce each other. Likewise, we will have a circle of such points about C as a center where reinforcement will take place so that there will be a bright circular fringe. From the center out to the edge then, there will be a number of bright and dark circular fringes. At the center, where the lens touches the plate, there will be a dark spot. This corresponds to the dark area seen in the thinnest part of the soap film just before it breaks. The rings nearer the center will be wider than those nearer the edge. This is due to the fact that as we get farther away from the center, the thickness of the wedge increases at a more rapid rate so that the points where interference and reinforcement take place are closer together thus making the rings narrower. Since the wave length of light at the red end of the spectrum is longer than at the violet end, the distance between the lens and the plate which will produce rein-

forcement of red light waves must be greater than for violet waves. Therefore the outer edge of each ring will be red and the inner edge will be violet with the other colors of the spectrum blending from one to the other between. It is interesting to note the effect of monochromatic light in producing Newton's rings. Red glass may be interposed in the beam of light coming from the source, so that only red rings will be seen. Then if the red glass is removed and blue glass is interposed, blue rings will be seen which have shrunk toward the center and are not as wide as the red rings. This is due to the shorter wave length of the blue light.

The number of rings which can be seen using white light is very small compared to the number which may be seen when monochromatic light is used. This is due to the fact that the red outside edge of one fringe tends to overlap the blue or violet inner edge of the next fringe which produces indistinctness. This overlapping increases as we come closer to the edge of the lens , and as a result, the outer rings disappear entirely. With monochromatic light, this overlapping is impossible, so that more rings will be seen. In his study of these rings, Newton found that the radii of the different rings for a given angle of incidence were proportional to the square root of the numbers 1, 2, 3, 4, ------. Thus the radius of the fourth ring is twice the radius of the first ring, and the radius of the ninth ring is three times the radius of the first ring. It should be emphasized that in all cases of interference produced by thin films, the character of the fringes varies greatly with the angle of incidence of the light falling upon the film and also with the index of refraction of the material of the film. Newton found the way in which the radii of the rings varied with the angle of incidence to a great degree

of accuracy considering the fact that he had very rough instruments to work with. He also made the first measurements of the wave length of light by the use of these rings, although he did not think of his measurements as wave lengths, because he believed in the corpuscular theory of light.

Newton's rings, as well as other interference bands, may also be seen by means of light which is transmitted through the plate and lens rather than reflected from them. In the case of reflection, as already mentioned, one of the wave trains suffers a phase change of half a period while the other does not, because they are reflected from mediums of different densities. But when the light is transmitted clear through the lens and plate, there is no reflection, hence no change of phase in either wave train due to reflection. Therefore, where a bright ring is seen by reflected light, a dark one will be observed by transmitted light. The colors of the rings will be complementary to the colors of the rings seen by reflected light. The center of the system will be marked by a bright spot instead of a dark one, and the red edge of each fringe will be on the inner side of the ring instead of on the outer side. Arago proved quite conclusively that the two systems of rings caused by transmitted and reflected light are complementary. He took a plate of glass and a convex lens and set them up as shown in Figure 13 on a sheet of uniformly illuminated white paper. Light from the paper

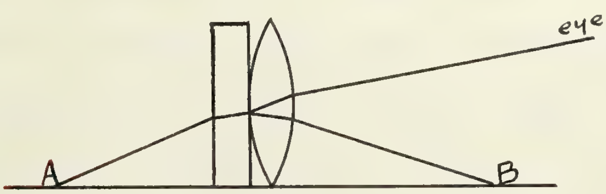

Figure 13.

at any point B on the same side of the plate and lens as the eye produced Newton's rings by reflection. Transmitted light from the

opposite side, such as at point A, produced the rings by transmission. Since these two systems of rings were complementary to each other, Arago predicted that uniform illumination would result if the field were viewed by reflected and transmitted light at the same time. His predictions were fully verified by the actual experiment.

Nature produces for us many very beautiful color effects due to interference from thin films. One of the most common examples is seen where there is a film of oil on the surface of water. Some of the light is reflected from the top surface of the oil film, while part of it is reflected from the lower surface, or the surface of the water. The oil film varies in thickness from place to place, so that different colors are reinforced at different parts of the film. If a very small drop of oil is placed carefully on the surface of very quiet water, it will spread out in the form of a circular film, being thickest at the center and gradually getting thinner towards the edges. It will thus produce Newton's rings quite perfectly. Usually however, the oil is distributed over the surface quite irregularly, so that there is no regularity of color arrangement.

Another example of this type of interference is often seen upon the surface of highly polished steel which has been exposed to the air for a few days so that a thin film of oxide has been formed upon it. The light is reflected from the surface of the film and also from the surface of the steel underneath, so that interference is produced.

V. Colors Of Thick Plates. Brewster's Bands.

Before taking up the theory of the interferometer, it will aid in understanding it to consider briefly interference produced

by thick plates. Sir David Brewster first made a study of this phase of the subject of interference in 1815. He used a device,

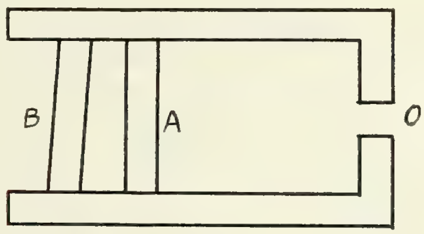

Figure 14.

the essential parts of which are shown in Figure 14. It consisted of a straight tube which was blackened on the inside. One end of the tube was closed except for a small opening O, through which light could be admitted. At the other end of the tube were placed two glass plates of equal thickness. The plates were placed very close together, and one plate A was set so as to be at right angles to the tube. The plate B was inclined at a small angle to A. This angle could be varied by means of a micrometer screw. When a beam of light passed through O, by looking in at the other end of the tube, Brewster observed interference fringes. The explanation of these fringes

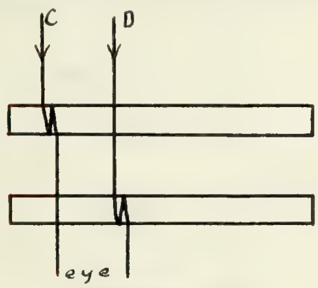

Figure 15.

is more easily seen by referring to Figure 15. Light coming from the direction shown by the arrows passes through to the lower surface of the plate A, is reflected back to the upper surface, and is again reflected downward passing out from A and directly through the plate B to the eye. A second wave train D passes directly through A on into B, is reflected from the lower surface of B to the upper surface, thence back again and out to the eye. Now it is clear that if the two incident wave trains are in the same phase and are parallel to each other, and if both plates are parallel to each other and have the same thickness, then the length of path for both wave trains is exactly the same, and they arrive at the eye in exactly the same phase causing reinforcement.

But if the plate B is inclined to A at a small angle, the thickness of glass through which the wave trains pass in the plate B is slightly greater than in A. The path followed in the reflections between the surfaces for the wave train D is therefore a little greater than for the reflections of the wave train C in the plate A. Therefore, the wave train D is retarded behind C, and they are thus in a condition to produce interference. Between two such plates, there may be several different combinations of reflected wave trains, all of which will produce interference. Figure 16 shows a few of the combinations which may take place. In Figure 15, the wave trains pass between the two plates only once. In Figure 16, the two sets of wave trains, A and B, pass between the plates three times, while the set C passes between the plates five times. Each of these different combinations will produce a system of fringes, and if conditions are right, these different systems may be seen at the same time. Brewster's bands may be very easily seen by setting up a simple apparatus such as is shown in Figure 17. Take two small plates of glass and lay them, one on top of the other, on a dark surface. Prop up a piece of ground glass at one side of the plates and at an angle of about 45 degrees with the surface of the table. The ground glass diffuses the light which passes through it from a sodium flame. With the eye in the position indicated so as to see

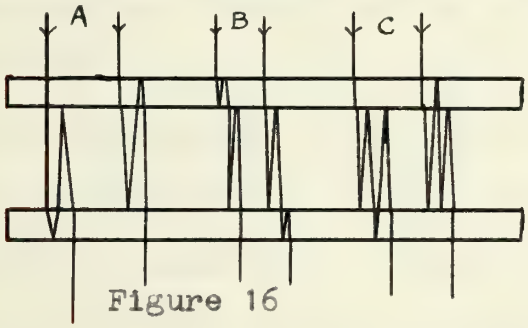

Figure 16

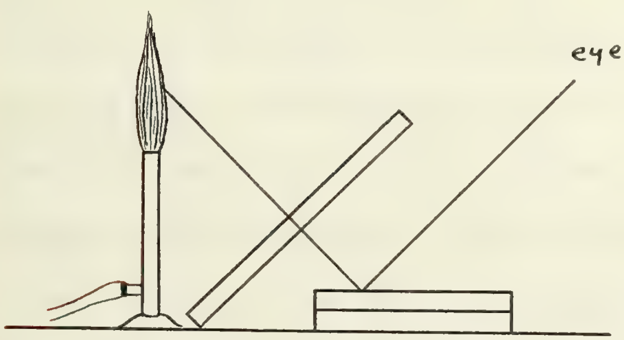

Figure 17.

the reflected light in the glass plates, a system of fringes will be seen on the field of light in the plates. These fringes may be either straight or curved. Since the plates are in contact with each other, their adjacent surfaces cannot be inclined to each other at an angle as suggested above in connection with Figures 14 and 15. Hence the fringes must be due to the fact that one plate of glass is slightly thicker than the other, and any single fringe will be the locus of all points at which the thickness of one plate differs from that of the other by a constant amount. This fact is often made use of to test the trueness of surface of a plate of glass. It is often desired to determine the constancy of the thickness of a large sheet of glass. To do this, a small square of glass is cut from the corner of the large sheet and laid upon the sheet. This is illuminated by a sodium flame, the light being incident at about forty five degrees. Usually a system of fringes will be seen. Let us suppose that there is a certain line across the large plate at all points of which the large plate is thicker than the small piece by a constant amount. If the little square is moved along this line, the fringe produced by the difference in thickness will remain in a fixed position. But it is assumed that we do not know where this line is, and we wish to trace it out. To do this, choose one of the fringes which is bright and easily seen. Then by trial, move the small square across the large sheet so that this particular fringe remains fixed in position. The small glass thus traces out a contour line of the large sheet at all points of which the large sheet has a constant thickness. By this method, a whole system of contour lines may be mapped out for the entire area of the large sheet of glass.

VI. The Michelson Interferometer.

Some very accurate measurements have been and can be made by the simple methods of producing interference already described, but the instruments of greatest precision which are based upon the principle of interference are known as interferometers. The best known and most widely used interferometer is that devised by Professor A. A. Michelson of the University of Chicago. It was originally designed by him for use in a very famous experiment to determine the ether drag or drift, which he and Morley performed, an account of which was published in 1886. The most common form of this instrument is shown in Figure 18. Suppose that we have a source of monochromatic light S, say a sodium flame, passing through a lens L which renders the rays of light parallel. These rays strike a glass plate M at an angle of forty five degrees and are transmitted through it to the half silvered surface AB. Here half of the light is reflected to the mirror P which is heavily silvered on the front surface. This light is then reflected directly back to M and is transmitted through to the eye. The other half of the light passes through the half silver film to the mirror O which also reflects the light directly back to M where the half silvered film reflects it to the eye. Thus the eye receives wave trains which have passed over

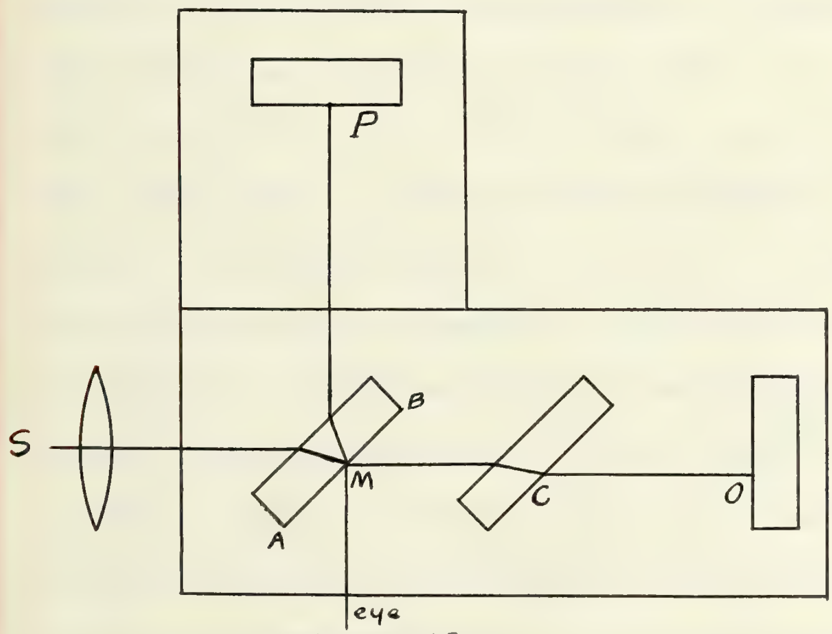

Figure 18.

two different paths, one from M to P and back, the other from M to O and back. These paths will hereafter be designated as MPM and MOM. From the figure, it is seen that any ray of light from S which is reflected by the half silvered film up to P and back again to the eye must pass through the glass plate M three different times. Also any ray which passes through to O and back and is then reflected to the eye, passes through M only once. Hence the ray MPM passes through three times as much glass as the ray MOM, and this will mean a large difference in the optical path of the two rays of light. To compensate for this, another plate of glass C, known as the compensator, is placed in the path of the ray from M to O and back. This plate is not silvered on either side, but it is cut from the same piece of worked glass that M is cut from, hence it has the same thickness. It is set on the support in the same angle as M, so that the ray MOM travels through exactly the same thickness of glass as the ray MPM. The mirror P is rigidly mounted on a heavy steel slide which is made to slide along very accurately ground steel ways by means of a long screw having a pitch of one millimeter. To the end of this screw is attached a steel disk of four or five centimeters diameter, its edge being marked off into 100 equal divisions. Thus, when the screw has made one complete turn, the mirror P has moved either forward or backward a distance of one millimeter. By means of the graduations on the disk, the screw may be made to turn through .01 of a turn thus moving the mirror .01 of a millimeter. The screw may be turned quite rapidly by a small crank at the end. But in addition to this, there is attached to the screw as an axis a worm wheel in the teeth of which a worm screw can be engaged at will. By turning the worm screw by means of a milled

head, the large screw can be turned very slowly. When the worm screw has made one complete revolution, the large screw has passed through .01 of a turn. The worm screw is also equipped with a head which is divided into fifty equal parts. therefore when the worm screw has moved through a distance equal to one half of one of these divisions, the mirror P has moved through a distance of .001 millimeter. Therefore, we can measure the distance through which P moves very accurately to thousandths of a millimeter, and by estimating tenths of a division, readings to one ten-thousandth of a millimeter may be made. When the screws are clean and in good condition, so that there is no lost motion, this type of interferometer is one of the most accurate instruments of measurement known. The plate M is held in a metal frame which is rigidly attached to the base plate. The compensator C is held in a metal frame which can be turned through a small angle so as to keep C adjusted parallel to M. The mirror O is held by springs against two adjusting screws which are set in a vertical plate immediately behind O. These screws are used to get the instrument in adjustment so that the fringes may be seen.

How are the fringes produced with the Michelson interferometer? When the mirrors O and P are rigorously perpendicular to each other and are both the same distance from the silver film AB, the image of O in AB will coincide with P. But if they are not exactly perpendicular, the reflected image of O will form a very small angle with P thus producing a condition similar to that of the air wedge described on page 16, Figure 11, and interference fringes will be seen. If the mirrors are not exactly vertical, fringes will appear again, but they will be perpendicular to those formed when the mirrors are not perpendicular.

Again, if the two mirrors are unequal distances from AB, then the rays of light will converge from all points of the mirrors as they come nearer the eye, and the paths of the different rays will therefore be of unequal lengths, and there will be interference, this time in the form of circular fringes. Thus we may see vertical, horizontal, or circular fringes depending upon the relative positions of the two mirrors O and P.

Let us consider for a moment a particular bright fringe seen in the field. We know that for this fringe, the paths traveled by the two rays of light MOM and MPM are such that the rays reinforce each other. Now if the mirror P is moved forward a very small distance, the length of the path MPM has been so changed that the wave train passing over it now interferes with the wave train passing over the path MOM, and we have a dark band where there was a bright one before. But the bright fringe has not disappeared. It has simply moved across the field a short distance. Thus, as the mirror P moves forward or backward, the fringes are seen to move across the field. If they are circular fringes, they will expand from the center if P is moving away from M, and will contract toward the center if P moves towards M. This fact is made use of in many experiments done with the interferometer some of which will now be described

VII. Some Actual Experiments Using The Interferometer.

A few experiments as actually performed with the interferometer will be described here.

1. Adjustment of the interferometer: In the more common experiments performed with the Michelson instrument, a sodium flame is generally used as the source of monochromatic light. A convenient method of producing such a flame is to take a square

piece of filter paper and roll it into a tube just large enough to slip over the tube of a Bunsen burner. Wrap the paper tube with ordinary grocer's twine so that it will hold its shape and then soak the tube in a solution of common salt. After soaking, it is allowed to dry. It may then be slipped over the Bunsen burner so that the edge of the paper projects a small distance above the mouth of the burner. When the burner is lighted, the paper burns, and the salt causes the flame to be a bright yellow which is the sodium flame. A paper tube made in this way will produce a sodium flame for several hours.

Now set up a convex lens between the flame and the plate M of the interferometer, placing the flame so that it will be in the focal point of the lens. (Figure 18). Wave trains coming from the flame will thus be rendered parallel by the lens and will strike the mirror M in parallel lines. By means of a small piece of wax, stick a pin to the lens, so that the point projects down into the path of the light coming from the flame. The mirrors O and P should be as nearly as possible the same distance from M. The distance of O from M may be roughly measured by means of a meter stick, and P may be moved by means of the screw until it is the same distance from M. Then by placing the eye in the position shown in Figure 18, four images of the pin will be seen as shown in Figure 19. Two of the images will be quite plain, and two will be dim. By means of the two adjusting screws at the back of O, it may be moved through a small angle so that the dim images of the pin will coincide exactly with the darker images. When this coincidence takes place, the fringes will appear. Then by a few adjustments of the screws, they may be made circu-

Figure 19.

lar, horizontal, or vertical as desired, and their width may also be varied.

2. Measurement of the wave length of sodium light.

The wave length of light is usually measured in Angstrom units. Such a unit is defined as being equal to 10^{-8} centimeter, or .00000001 centimeter.

Let us fix our attention upon one particular bright fringe in the field of view. Now if we move the mirror P forward so that the fringe has been displaced, and the next adjacent bright fringe has moved into its place, then the difference in path between the two rays MOM and MPM has been changed by one whole wave length. This is equivalent to saying that the path MPM has been shortened one whole wave length. But the light is traveling over the path from M to P, and then back to M, or in reality, it passes twice over the same path. Hence to change the path one whole wave length, the mirror P moves through a distance of only a half wave length. Now by means of the small worm gear and screw, the mirror may be moved forward slowly. During this motion, count the fringes which pass a given point in the field of view. Let us say that 100 fringes have passed across the field. We may read the distance through which the mirror has moved from the graduations on the head of the screw. This distance multiplied by two and divided by 100 gives the wave length of the light used. The following results were observed for a sodium flame. The column headed D gives the distance in centimeters through which the mirror P moved. The next column gives the values of 2D, the third column, N, gives the number of fringes counted, and the fourth column headed l, gives the wave length which is gotten by use of the equation

$$l = 2D/N \qquad (8)$$

The fifth column gives l in Angstrom Units.

D	2 D	N	l (2D/N)	l
.002950	.005900	100	.00005900	5900
.002963	.005926	100	.00005926	5926
.002935	.005870	100	.00005870	5870
.002946	.005892	100	.00005892	5892
.002945	.005890	100	.00005890	5890

The average of these results is 5895.6 Angstrom units. Sodium light consists of waves of two slightly different lengths. The wave length of the shorter sodium waves is generally given as 5890.22 Angstrom units, and for the other component, the wave length is 5896.18 Angstrom units. Thus it is seen that the value obtained above agrees very closely with the generally accepted values.

In order to get accurate results in this experiment, care must be taken that all lost motion of the screw is taken up before counting of the fringes is begun. Any lost motion will introduce considerable error. This is not a difficult experiment to do once the interferometer is adjusted so that the fringes are sharp. It is however rather tedious, and is very tiring to the eyes.

3. Ratio of the wave length of the D lines.

The fact was brought out above that sodium light is composed of two different wave lengths. When sodium light is allowed to pass through the slit of a spectroscope, the prism refracts these two different wave lengths through slightly different angles, so that two yellow lines are seen. These lines are known as the D lines, the one having the longer wave length being the D_1 line, and the other the D_2 line. Let the wave length of the

D_1 line be l_1, and that of the D_2 line be l_2. The interferometer furnishes a means of determining the value of the ratio $\frac{l_1}{l_2}$.

The theory is as follows: Suppose that the paths of the two wave trains of light in the interferometer are exactly equal, and that the light is coming from an absolutely homogeneous source, that is, a source which sends out waves of one definite wave length only. This set of waves will produce only one set of fringes, and in this case, the mirror P may be moved any distance without destroying the fringes. But such a source of light is very difficult to realize or obtain. If sodium light is the source, we have two different wave lengths producing fringes. Now when the two paths MOM and MPM are equal, or in other words, when the difference in path is zero, then the fringes formed by one wave length will coincide with those of the other wave length. But as the mirror is moved, or the difference of path is changed, both sets of fringes will move across the field of view, but one set will move across the field more rapidly than the other. When the difference in path has been increased the proper amount, one set of fringes will have gained on the other set by half a fringe, which means that the fringes of one set will occupy the dark spaces between the fringes of the other set. When this occurs, if the intensity of the light for both sets of waves is the same, the fringes will disappear, because one set completely illuminates the dark spaces between the other set. But if they are not of the same intensity, then both sets of fringes may be seen, but they will both be dimmed. Now when one set has gained half a fringe on the other, the difference in path of MPM and MOM contains half a wave length more of the shorter waves than the longer ones. That is, if the difference in path contained 1000 of the longer wave lengths, it

would contain 1000.5 of the shorter ones. Let N be the number of D_1 waves of length l_1 contained in the difference of path. The difference of path will then be equal to Nl_1. Let N + .5 be the number of D_2 waves of length l_2 contained in the same path difference. Then the path difference is also equal to $(N + .5)l_2$. Therefore we may write

$$Nl_1 = (N + .5)l_2 \qquad (9)$$

But to produce any given difference of path, we have seen that the mirror P moves through only half that distance. Then

$$\frac{Nl_1}{2} = \frac{(N + .5)l_2}{2} \qquad (10)$$

Dividing through by l_2, we have

$$\frac{Nl_1}{2l_2} = \frac{(N + .5)}{2}$$

And dividing through by N/2 gives

$$\frac{l_1}{l_2} = \frac{N + .5}{N} \qquad (11)$$

which gives the ratio of the wave lengths of the two D lines of sodium light. In the actual manipulation of the experiment, the difference in path is made zero by moving the mirror P to a position where it is the same distance from M that O is. The two sets of fringes are then coincident and brightest. Then move P slowly either forward or backward, until the fringes disappear or are dimmest, counting the fringes which cross the field during the movement. The number counted will give the value which must be substituted for N in the equation above to give the value of the ratio l_1/l_2.

The following results were observed:

N	l_1/l_2
497	1.001006

N	l_1 / l_2
504	1.000991
490	1.001020
489	1.001022
493	1.001014
506	1.000988
487	1.001026
498	1.001004
499	1.001002
491	1.001018

The mean value of these results gives $l_1 / l_2 = 1.0010091$. If we take the wave length of the D_1 line as 5896.18 and of the D_2 line as 5890.22, we have $\frac{l_1}{l_2} = \frac{5896.18}{5890.22} = 1.0010101$

These two results vary from each other by one part in one million. A study of the separate readings however does not show this close agreement. This discloses the fact that there are some difficulties in making the experiment. The chief difficulty is in the inability of the eye to tell when the fringes are dimmest, in other words, when there is least visibility. This is shown in the marked variation in the values of N. Another difficulty lies in the fact that as the position of lowest visibility approaches, the fringes become so dim that they are exceedingly difficult to count. Hence the desirability of taking a large number of readings by which the errors in some will counteract the errors in others.

The value of the interferometer in spectroscopic work is not so clearly demonstrated by this experiment as it is by the inversion of this process. If, when light passes through the

interferometer, this change in the visibility of the fringes occurs with the change in path difference, then we may be sure that the source is composed of waves of different wave lengths. Thus, the interferometer is of great value in spectroscopic work in analyzing the various lines of the spectrum into their components. Some of the lines are much more complex than the sodium line, and are made up of a number of different wave lengths. But Michelson, with his interferometer and with a machine of his own design called the harmonic analyzer, has done some very noted work in separating lines of the spectrum into their components, which could not be separated by the best of grating spectroscopes. His harmonic analyzer is a machine which automatically draws what are known as "visibility curves" for the various spectral lines as they are seen through the interferometer. A study of these curves shows the composite character of the lines, but it takes one expert in the method to get the full meaning from the curves. The method is more fully described in Michelson's book entitled Light Waves And Their Uses. The Michelson interferometer however is not so well adapted to spectral analysis work as the Fabry-Perot interferometer which will be described farther on, and its advantages in this kind of work will be then pointed out.

4. Measurement of the index of refraction.

We have already seen that the fringes formed by two different wave lengths overlap each other for a certain path difference. If the source is white light, we have all colors of the spectrum, or all the wave lengths from the longest to the shortest. The fringes formed by all these different wave lengths will coincide when the path difference is zero, but when the mirror P is moved in either direction, the shortest wave lengths soon gain half a

fringe over the longest, and the fringes disappear entirely. This will happen when the mirror is moved a very small fraction of a millimeter. The appearance of white light fringes therefore furnishes a very accurate means of telling when there is no difference of path, or when MPM and MOM are equal. Let the interferometer be adjusted for white light fringes. Now if a glass plate is placed in the path MPM, the effect is to increase the path as if the mirror P had been moved away from M, and the fringes will vanish. Now if the mirror is moved toward M, the path will be shortened, and when the decrease in path thus caused is equal to the increase previously caused by the glass plate, the white light fringes will reappear. Now the velocity of light through glass is slower than it is through air. If the velocity in glass is V_2, and in air V_1, the velocity in glass is V_2 / V_1 times V_1. This decrease in velocity corresponds to an optical path of V_1 / V_2 times the thickness of the glass. This ratio V_1 / V_2 is called the index of refraction of the glass, and it may be designated as m. Then if the thickness of the glass is t, the optical path through the glass is mt. If the glass were not in the path, the light would travel through a distance t in air which fills the space occupied by the glass. Therefore, the difference in path D caused by the glass is

$$D = mt - t$$

and solving for m, we have

$$m = \frac{D + t}{t} \qquad (12)$$

In the manipulation of this experiment, the interferometer is first adjusted for white light fringes. This is done by setting the mirror P as nearly as possible the same distance from M as

the mirror O. This may be done fairly well by simply measuring with a meter stick. Then with sodium light, adjust the mirror O by means of the adjusting screws so that the fringes are as distinct as they may be made. Now substitute white light for the sodium light, and with a slight turn or two of the worm gear wheel, the fringes should appear. Now mount the glass plate for which m is to be found in the path MPM, so that it just covers half of the field. The fringes will therefore disappear over that half of the field covered by the glass. Now move the mirror forward slowly, and when the distance moved has shortened the optical path as much as the glass has increased it, the fringes will appear again, but this time in the half of the field of view covered by the glass. The distance through which the mirror has moved may be read from the circular scale, which gives the value of D in equation (12). The thickness of the glass, t, may be measured accurately by means of a micrometer caliper, or better, by means of a spherometer which is graduated to thousandths of a millimeter. These values substituted in (12) gives the value of m.

Two sets of observations are given here, one for a microscopic cover glass which was .1675 millimeter thick, and the other for an interferometer plate which was 2.1536 millimeters thick. The values of D are also given in millimeters.

For the microscopic cover glass:

D	t	$m = \frac{D + t}{t}$
.0904	.1675	1.539
.0979	.1675	1.584
.950	.1675	1.567
.951	.1675	1.567

D	t	$m = \frac{D+t}{t}$
.0912	.1675	1.545
.0933	.1675	1.558
.0954	.1675	1.570
.0993	.1675	1.593
.0907	.1675	1.542
.0910	.1675	1.544

The variation in these results is rather large. This may be due in part to the fact that the glass was not of uniform thickness throughout which would produce considerable variation in the readings. Another precaution which is necessary to observe is to see that when the white light fringes reappear, that they be brought to the same position in the field. On their reappearance, they are apt to be dimmer and smaller than they were before the glass plate was placed in the path. After some practice, they can usually be brought very nearly to the same position. Another precaution to prevent error is to see that the plate is perfectly parallel to the mirror P. If it is inclined to it at a small angle, the thickness of glass through which the light passes will be greater than the measured thickness which is used in the equation.

The results for the interferometer plate, which was made of very fine glass and whose surfaces were accurately parallel, show much greater accuracy.

D	t	$m = \frac{D+t}{t}$
1.1995	2.1536	1.556
1.1998	2.1536	1.557
1.1930	2.1556	1.553

D	t	$m = \frac{D+t}{t}$
1.1901	2.1536	1.552
1.1959	2.1536	1.555
1.1996	2.1536	1.557
1.2016	2.1536	1.558
1.2007	2.1536	1.558
1.1973	2.1536	1.555
1.1989	2.1536	1.556

The per cent of variation between the largest and the smallest value of m given above is .38 of 1 %. These results are very consistent, so the mean result should give a very close value of m for this particular plate.

This method has been used to measure the index of refraction of various liquids and gases, and to show the change in m of a gas under varying pressures. The gas or liquid may be placed in a tube with glass ends, and the tube is then placed so that the ray MPM must pass through the tube. This causes a displacement of the white light fringes in the same way as the glass plate, and the calculations are very similar.

VIII. Some Famous Classical Experiments.

Consider again the equation

$$m = \frac{D + t}{t}$$

and solve it for t. Then

$$t = \frac{D}{m - 1} \qquad (13)$$

This equation suggests a method of using the interferometer for measuring the thickness of transparent substances. The procedure is similar in every way to that given above for determining m, but in this case, m is a known quantity, and t is the unknown. Since with the interferometer we are dealing with light waves

which have a very small length indeed, this method lends itself admirably to the measurement of very thin plates, such as the film of silver on a mirror or a soap film.

E. S. Johonnot, in an issue of the Philosophical Magazine of 1899, reported the results of an experiment in which he measured the thickness of the black spot of a soap film. He found that one soap film placed in the path of one of the interfering wave trains produced no appreciable displacement of the fringes. He therefore constructed a frame by means of which he could place as many as fifty soap films in a row in one path, and this produced a displacement of half a fringe. Johonnot calculated that when the film was thin enough to show the black spot, that it must not be composed of more than two layers of molecules. Therefore he took his measurement of the thickness to be the upper limit to the distance between the molecules of the substance. He showed the thickness of the film at its thinnest part to be about six millionths of a millimeter.

Michelson has made very good use of the interferometer in measuring very small angles which could not be measured in any other way. He has also used it to measure the coefficient of expansion of substances which could not be obtained in large enough bodies to make their expansion appreciable by any other method. The interferometer has also been used in connection with a very delicate balance by which the gravitational force exerted by a large lead ball upon a small one could be measured. The force to be measured was about one twenty millionth of the weight of the small lead ball, a force which could not be measured by an ordinary balance even when a microscope was used in connection with it. The interferometer has also been used to test the accuracy of

very fine screws such as those used in dividing engines with which fine diffraction gratings are ruled. Such a screw must be very accurately turned.

Aside from these valuable uses which Michelson has made of the interferometer, he has performed what may be termed some very startling experiments with it. He has measured the diameter of the great star Betelgeuse disclosing the fact that it is a heavenly body the size of which is beyond the power of the most vivid imagination to conceive. One of Michelson's most famous experiments is that in which he determined the length of the standard meter in Paris in terms of the wave lengths of the red, blue, and green spectral lines of cadmium. By an ingenious modification of the interferometer, he succeeded in getting very accurate and consistent results. The readings were taken by Michelson and two other observers, and at wide intervals of time from each other, which makes the very consistent results which they obtained even more convincing. They found that the number of light waves in a standard meter was, for the red cadmium line, 1,553,163.5, for the green, 1,966,249.7, and for the blue, 2,083,372.1. They found that the absolute accuracy was about one part in two million.

One of the most important and interesting problems which many eminent scientists have attempted to solve is that of the "ether drift". It was pointed out in the early part of this discussion that there must be a medium by which light waves may be transmitted through space. This medium is known as the ether and it is characterized as an elastic solid. The problem of the "ether drift" is the question of whether the ether is carried along through space with the earth as it moves through its orbit about the sun, or whether the ether remains stationary with

respect to the earth. It was in an effort to solve this problem that Michelson invented the interferometer. In performing this experiment, he had the collaboration of Morley, and the results of their experiment were published in the Philosophical Magazine in 1887. An interferometer was built on a rather large scale. It was mounted on a stone which was about four feet square and one foot thick, and this stone was mounted on a block of wood which was floated in a tank containing thirteen tons of mercury. This rendered the instrument free from all minor vibrations and made it possible to turn the interferometer through an angle of ninety degrees without getting it out of adjustment. Light coming from the source was divided by a half silvered mirror into two beams at right angles to each other, and these beams were reflected back and forth several times between a series of mirrors mounted at the four corners of the stone. By this large number of reflections, the beams were made to travel over a path of about ninety feet. The beams were finally brought together again and reflected into a telescope where they were in a condition to interfere, and interference fringes were produced. Michelson predicted that if the ether did not move with the earth through its orbit, there would be a displacement of half a fringe when the interferometer was rotated through ninety degrees. The instrument was set so that one of the beams of light was in the direction of motion of the earth in its orbit, and the other beam was at right angles to this motion. Then when the interferometer was turned through an angle of ninety degrees, the two beams were interchanged with respect to the motion of the earth. If the ether were stationary, this would cause a retardation of one beam behind the other so

as to cause the displacement of fringes. The observations were taken at different times covering a period of a year so as to make sure that the motion of the earth was not in any way affected by the attraction of any other heavenly body. The predicted displacement of the fringes however was not observed. The natural conclusion to draw from the results is that the ether moves along with the earth in its orbital motion, but there have been some other hypotheses suggested to explain the negative results obtained. One of them is based upon the theory of relativity which assumes that a body in motion is shortened if its length lies in the direction of motion. If this theory is true, the beam of light lying in the direction of motion of the earth's motion would travel over a shorter path because of the shortening of the apparatus in that direction which would account for the results which Michelson and Morley obtained without discrediting the theory of the ether drift. Michelson has been working on the problem during the last year (1921), and it is hoped that the results obtained from his more recent work will throw considerable light upon the whole subject of the theory of relativity.

IX. Other Types Of Interferometers. The Fabry-Perot.

Next to the Michelson interferometer, the most widely used instrument is the Fabry-Perot interferometer. It is very simple and consists essentially of two plates of glass, each one being half silvered on one surface. The plates A and B (Fig. 20) are mounted on a support so that their silvered surfaces are facing each other. We shall first suppose that the two plates are not exactly parallel to each other. Let S be

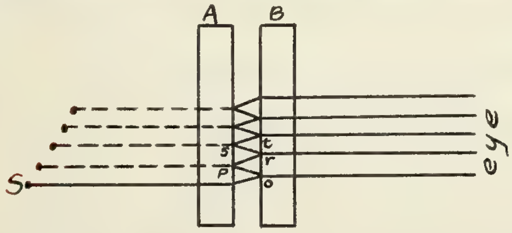

Figure 20

a very narrow slit illuminated by monochromatic light. The light will pass to the two plates, and part of it will be transmitted directly to the eye. Another part will be reflected at o back to p, where it will be reflected again back to r. Here a part will be transmitted to the eye, while another part will again be reflected to s and then back to t. These reflections between the plates will be numerous, and the eye will see a number of images of the slit arranged side by side and parallel to the real slit. Now if the mirrors are adjusted so as to be parallel to each other, these images will all coincide with each other. But the light which reaches the eye from the first image has traveled over a path which is shorter than the path of the light from the second image by a distance equal to twice the distance between the plates. Similarly, the light from the second image has traveled a shorter distance than that from the third, and so on. The wave trains from these images are therefore in a condition to interfere if the plates are parallel. When they are very nearly parallel, the fringes will be straight and very fine and narrow. As exact parallelism is approached, they will become wider, and when the plates are exactly parallel, they will be circular. Due to the large number of reflections, the fringes are very narrow, and the dark bands between are very wide. This constitutes an advantage over the Michelson instrument especially in spectroscopic work. It was mentioned on page 40 that when the source of light for the Michelson interferometer is of a composite character, there are points or positions of the mirror P at which the fringes caused by one wave length fill the space between the fringes due to the other wave length, and in this case, the

fringes become very dim or else disappear entirely. For this reason, it is very difficult to determine the position of the mirror P for which the visibility of the fringes is lowest. But with the Fabry-Perot instrument, as just pointed out, the dark space between the fringes is very wide compared to those of the Michelson interferometer. Therefore when light of two different wave lengths is used and the shorter one has gained half a fringe over the longer one, the fringes of the shorter wave length stand out very clearly in the spaces between the fringes of the other wave length. Hence the value of N in equation (11), page 38, can be much more accurately determined with the Fabry-Perot interferometer.

In using this instrument, the light is generally passed through a prism first, and only light from one line of the spectrum thus produced is allowed to pass through the plates, which makes the light as nearly monochromatic as possible. The adjustments necessary to see the fringes are however very tedious, and it requires considerable practice and patience to become accustomed to the instrument.

2. Jamin's Refractometer.

The interferometer devised by Jamin was made especially to measure the index of refraction of gases and liquids, and is therefore most commonly spoken of as the refractometer. It is based upon the principle of interference by thick plates as explained on page 26. Two plates of

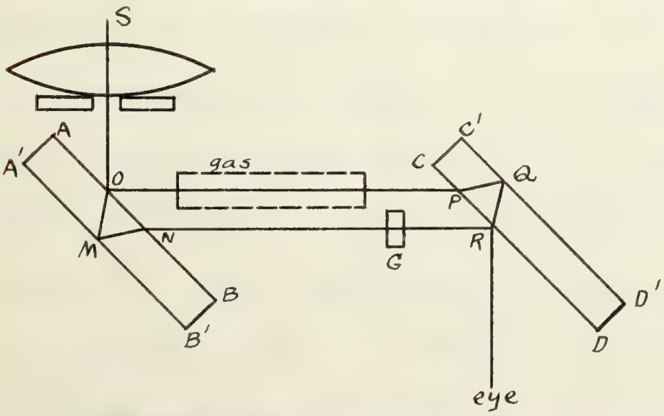

Figure 21.

parallel surface glass of equal thickness, usually about one centimeter, are mounted parallel to each other on an optical bench as shown by AB and CD in Figure 21. The plates are mounted vertically, so that in the diagram, they are shown as perpendicular to the plane of the paper. Each plate is silvered on its back surface. Light from a source S passes through a lens which causes a parallel pencil of rays or wave trains to fall upon the plate AB at O at an angle of forty five degrees. Part of this light is reflected from the front surface over to the point P at the front surface of the second plate. It is here transmitted to the back surface where it is reflected downward at Q and emerges from the plate at R. A second part of the light from S upon striking AB at O is transmitted to the back surface where it is reflected at M to N of the front surface and thence to R on CD where it is reflected again. Thus the beam from S is divided into two beams as they pass through and between the plates only to be reunited again as they leave the second plate at R. Now if AB and CD are rigorously parallel to one another, the paths of the two beams will be equal to each other, and the beams will emerge at R in the same phase and therefore in condition to reinforce each other. In this case, the field of view will be uniformly illuminated, provided the plates are perfectly plane. But suppose that the plate CD is inclined to AB by a very small angle. Then the path of the wave train OPQR will be slightly different from that of OMNR, and they will emerge at R in opposite phase causing interference fringes to appear in the field of view. The plate CD is mounted in such a way that it can be controlled by two screws, one of which moves it about a vertical axis while the other moves it about a horizontal axis. These screws are graduated so that

the angle through which the plate moves can be read directly from the instrument. If the instrument is adjusted so that the fringes are seen, and a piece of glass is then placed between the plates and in the path of only one of the beams, this beam will be retarded by the glass, and the fringes will be displaced a certain amount as the result. Jamin made use of this fact to measure the index of refraction of various gases. He placed a tube containing a gas, the index of refraction of which he wished to determine, in the path of one of the beams, say OP, (Fig. 21) which retarded that beam a certain amount behind the beam NR thus causing a displacement of the fringes. Now by putting a piece of glass of the proper thickness in the path of the beam NR, it could be retarded an equal amount, so that the fringes would be returned to their original position, or if tube and glass are placed in position at the same instant, the fringes would not be displaced at all. Then, the index of refraction of the glass being known, the retardation which it causes can be calculated. This will be equal to the retardation caused by the gas in the tube, and from this fact, its index of refraction may be determined. The glass used (G in Fig. 21) is known as the compensator. It is evident that for different gases, the compensator would have to be of different thicknesses. It would be a very tedious process to try one piece of glass after another until one of the right thickness was found. Jamin's original compensator consisted of a single piece of glass mounted upon a vertical axis. By turning the plate on its axis through an angle, the thickness through which the light passes could be varied as

Figure 22.

much as desired. A better form of compensator is illustrated in Figure 22. It consists of two very slender prisms whose angles are equal, and which are placed one upon the other so that their edges are opposite each other. In such a position, they form a parallel plate, and by means of a screw, one prism may be slid along the other thus varying the thickness of the plate at will. Such a compensator can be calibrated for the various relative positions of the two plates, and when calibrated, it is very useful in making experiments with the Jamin refractometer.

3. Lodge's Interferometer.

The principle of the Lodge interferometer is easily understood by a study of Figure 23. Three glass plates AB, C, and D are used and set up as shown. The plates C and D are inclined to AB at an angle of forty five degrees. The plate AB is half silvered on the surface next to the source of light S.

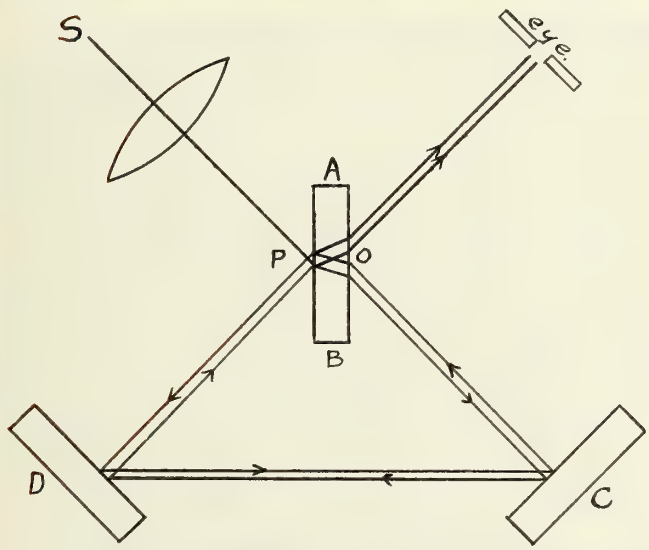

Figure 23.

C and D are heavily silvered on their front surfaces. Light from the source S strikes the half mirror AB at P. Part of it is reflected and passes along the sides of a triangle between AB, D, and C as shown by the arrows. The other part is transmitted transmitted through AB at P and passes around the same triangle but in the opposite direction. Both wave trains, after passing around the triangle in opposite directions, emerge in the same direction at O in a condition to produce interference. The fringes

are seen by the eye through a very small opening such as a pinhole, or elseby means of a telescope. When C and D are exactly the same distance from the half silvered surface of AB, the reflected image of C will appear to the eye to coincide with D. Now if C is moved forward a very small distance, there will be a virtual air wedge between the image of C and the actual surface of D. Interference is thus caused in exactly the same manner as with the Michelson interferometer, and the fringes formed will be either circular, vertical, or horizontal depending upon the angle be tween the two mirrors C and D. Lodge used his interferometer in an experiment to determine if there is an ether drift. He mounted the instrument betweentwo circular steel plates of large diameter which were whirling as rapidly as they could be made to whirl without flying to pieces. If the ether was given a motion by the spinning disks, Lodge predicted that there would be a displacement of the fringes seen in his interferometer, because the velocity of the light would be accelerated in one path and retarded in the other by the moving ether. But after all spurious effects were done away with, there was no displacement of the fringes observed. The conclusion was that there was no drag of the ether along with the moving body, at least in the case where such a small moving body was used.

There are still other types of interferometers which might be described here, but they are all based upon principles very similar to those already described here, and none of them is as widely used as the Fabry-Perot and Michelson instruments. One interferometer manufactured by Ph. Pellin of Paris is known as the Fizeau instrument. It makes use of the principle of Newton's rings, and is principally used as a dilatometer. Another inter-

ferometer due to Lummer and Gehrke is similar in principle to the Fabry-Perot instrument except that the multiple reflections are made to take place between the two surfaces of a single plate of glass rather than between adjacent surfaces of two separate plates.

X. Conclusion.

Books might be written upon the subject of interference and its applications and measurement without going over the same material twice. It is hoped that what has been presented here will acquaint the reader with the elementary principles and applications of the interference of light, and that a desire may be kindled in him to explore further this interesting field of Science. For further reading on the subject, the following books are recommended:

Michelson - Light Waves And Their Uses.

Maclaurin - Light.

For the more theoretical aspects of the subject, the following are good:

Edser - Light For Students.

Preston - The Theory Of Light.

Wood - Physical Optics.

For directions as to performing various experiments in interference, see -

Clay - Treatise On Practical Light.

Mann - Applied Optics.

The original works of Young and Fresnel are very interesting for the light which they throw upon the history of interference and of the wave theory of light.

I wish to acknowledge my indebtedness to Dr. W. F. Schulz of the Department of Physics of the University of Illinois for many valuable suggestions given and for his interest in the work of preparing this thesis; also to Professor A. P. Carman, head of the department, who suggested the topic and gave me much encouragement during the progress of the work.

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